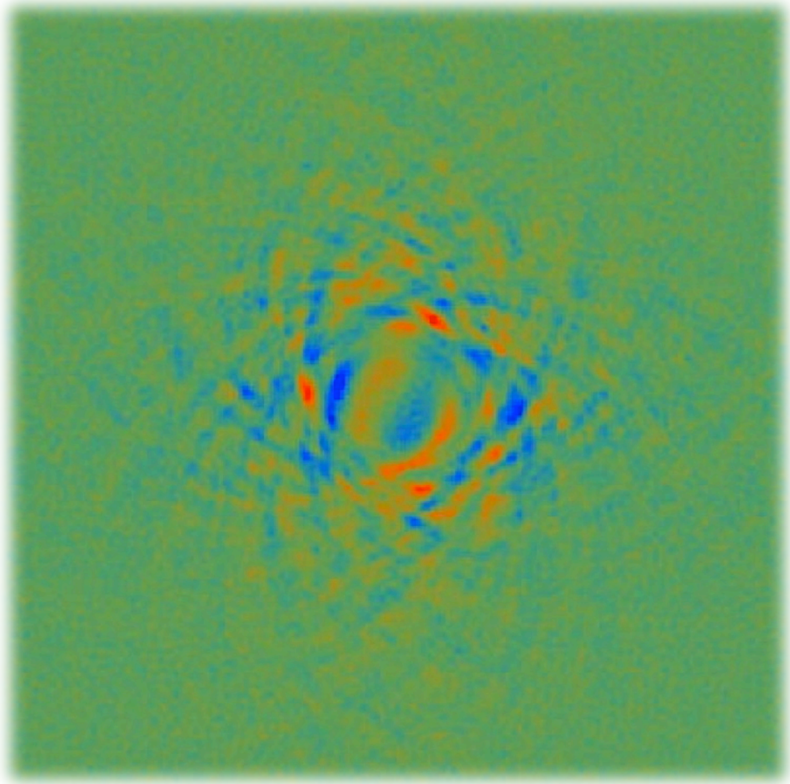
Physics with Future CMB Surveys



Blake D. Sherwin

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ACT/Simons Observatory/CMB-S4/LiteBIRD Collaborations

Outline

I. Inflation via B-modes

II. Neutrino properties via CMB lensing

III. Light particles via small scale CMB

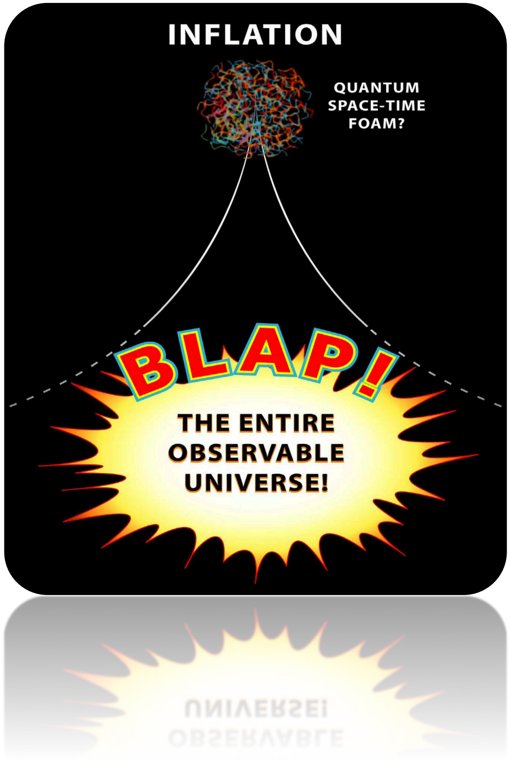
IV. Experiments: S4 and Beyond

The Physics of Inflation from the CMB

- Inflation: initial phase of accelerated expansion with shrinking horizon – explains flatness + fluctuations

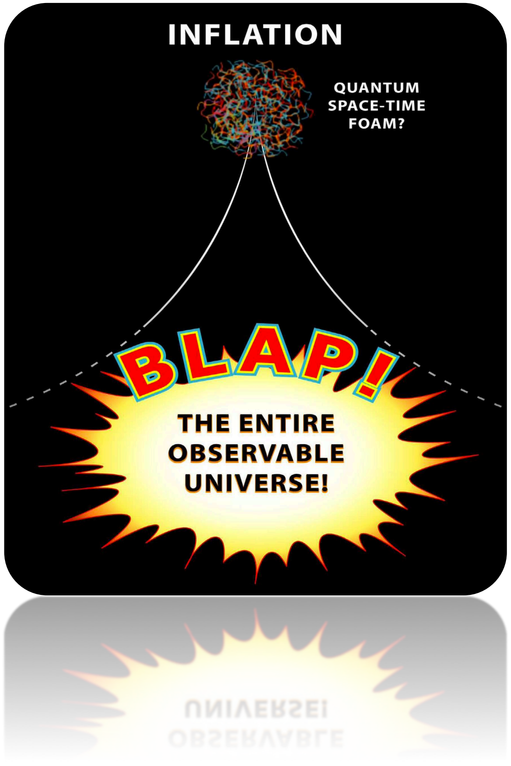
- Well tested for density fluctuations

- Many models of inflation produce inflationary gravitational waves. Strength: parameterized by tensor/scalar ratio r



The Physics of Inflation from the CMB

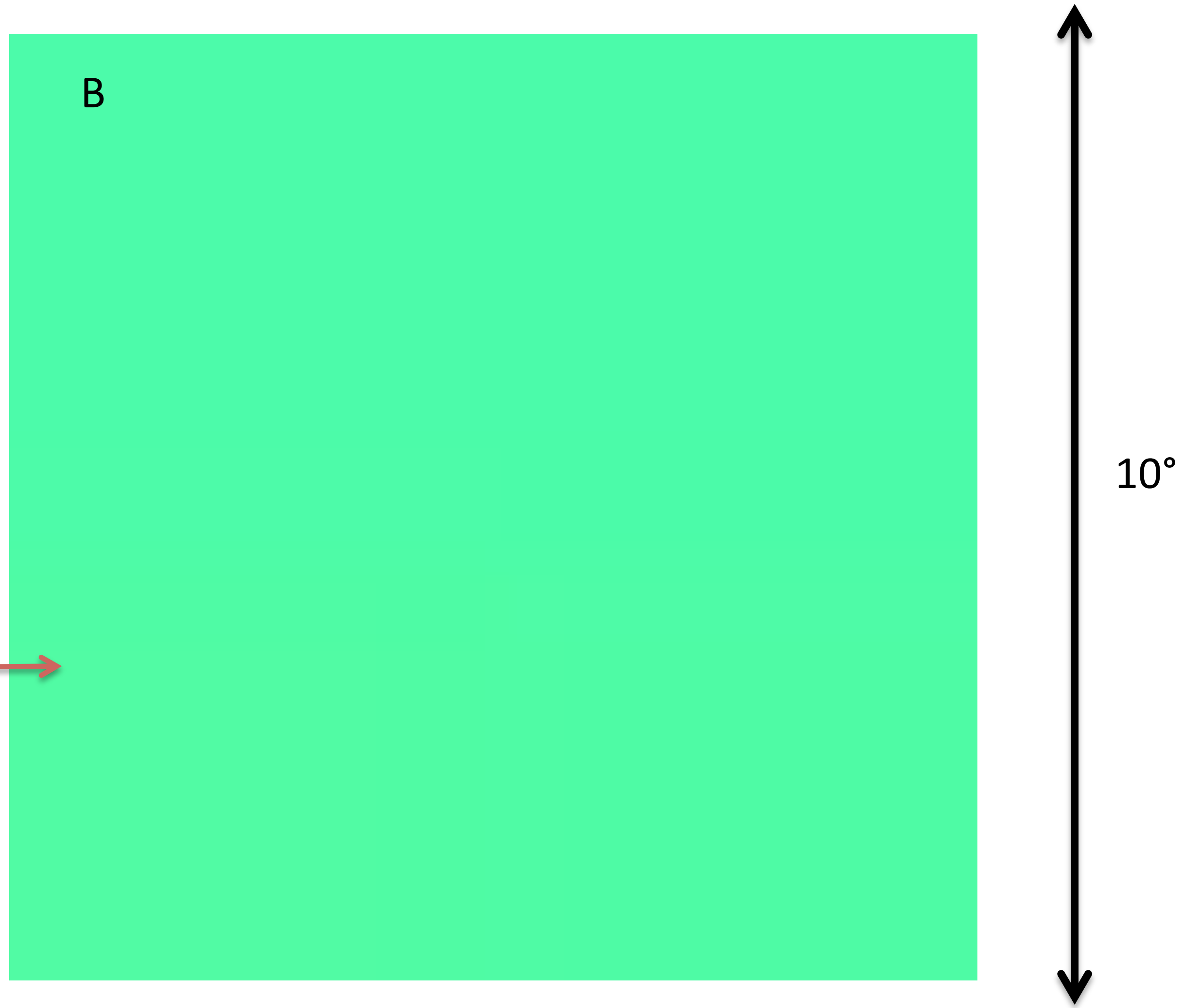
- Detection: confirm inflation paradigm; strength tells us the *energy scale*
- Even improved upper limits on r very interesting. Target: ruling out r>0.001 will exclude large field models
- Best way to detect inflationary GWs: CMB. Not T or E-polarization, but characteristic CMB B-polarization

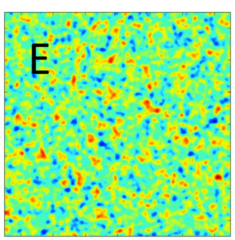


CMB B polarization* with r = 0

B-mode polarization: no leading order signal from scalar density perturbations!

B-modes are a “null channel”

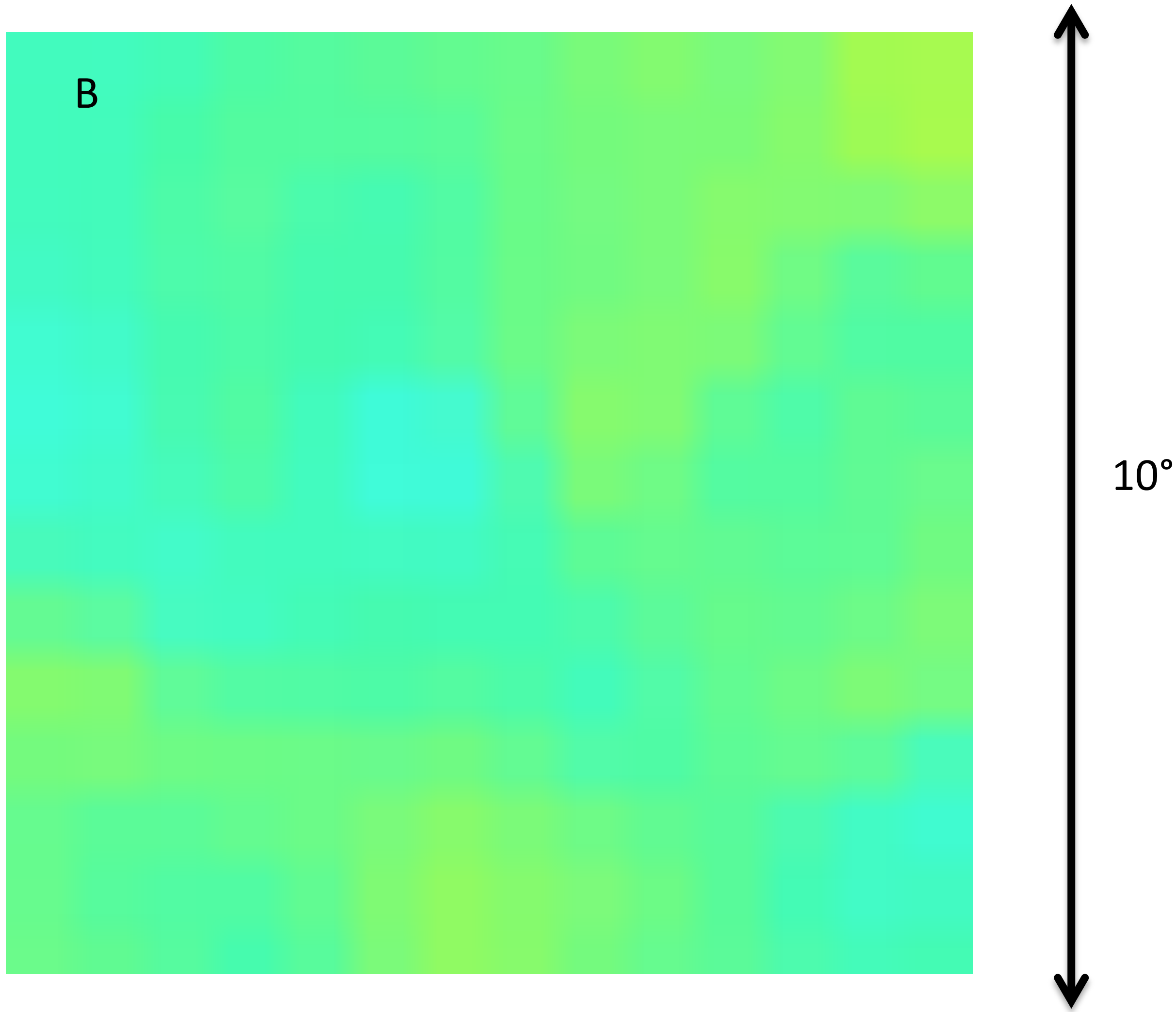


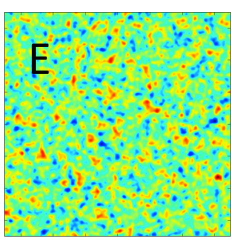


CMB B polarization* with r>0

See r clearly as there is no background cosmic variance from normal (scalar) density perturbations

Limits: σ(r)<0.1





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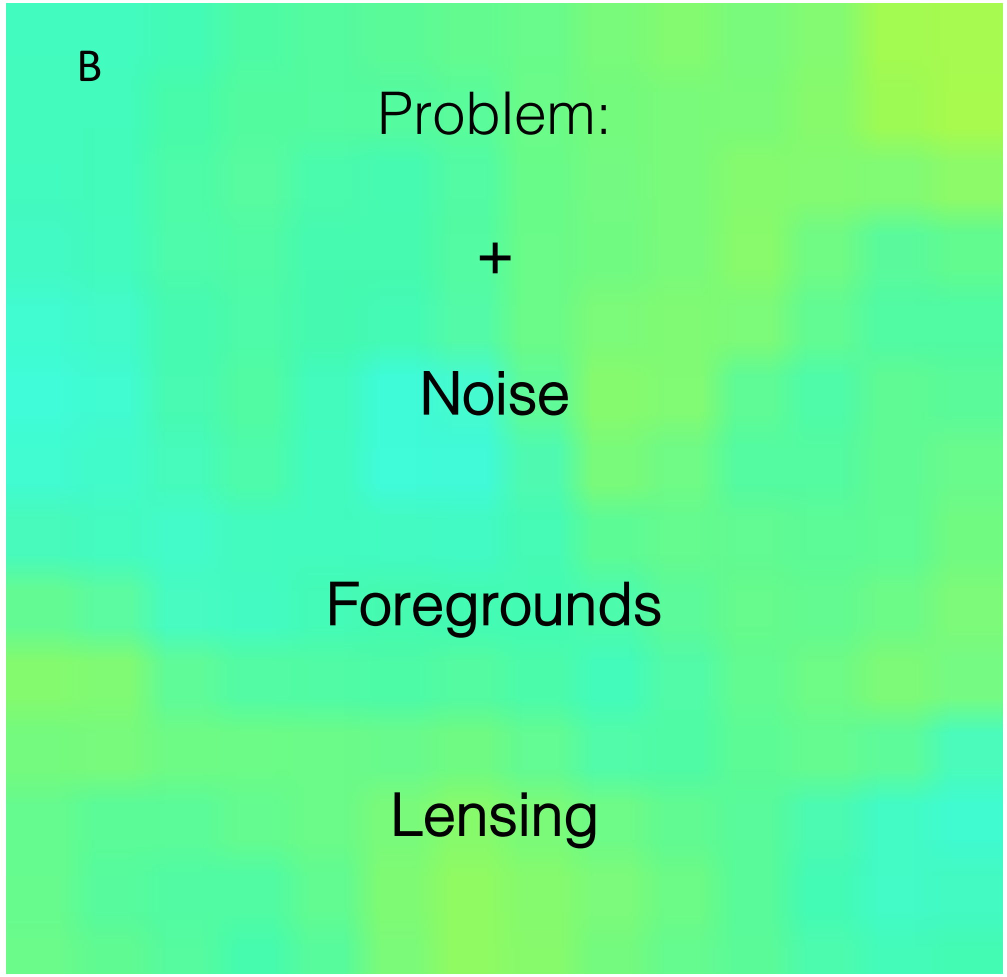
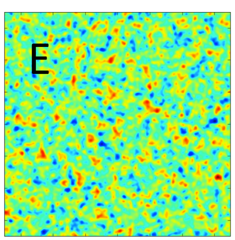


10°

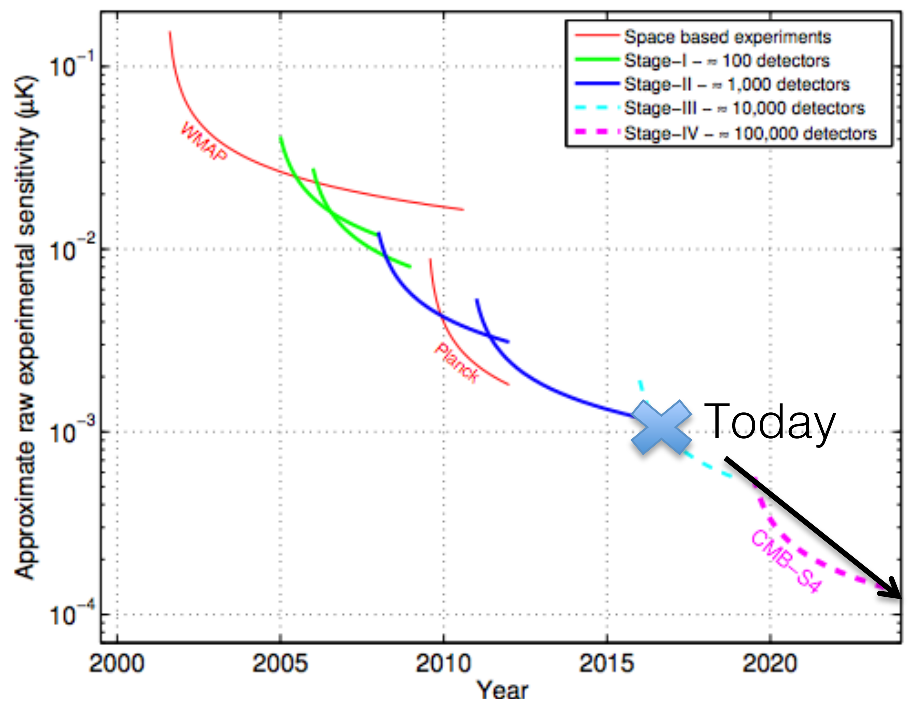


What is needed to reach r~0.001?

(2 orders of magnitude improvement)

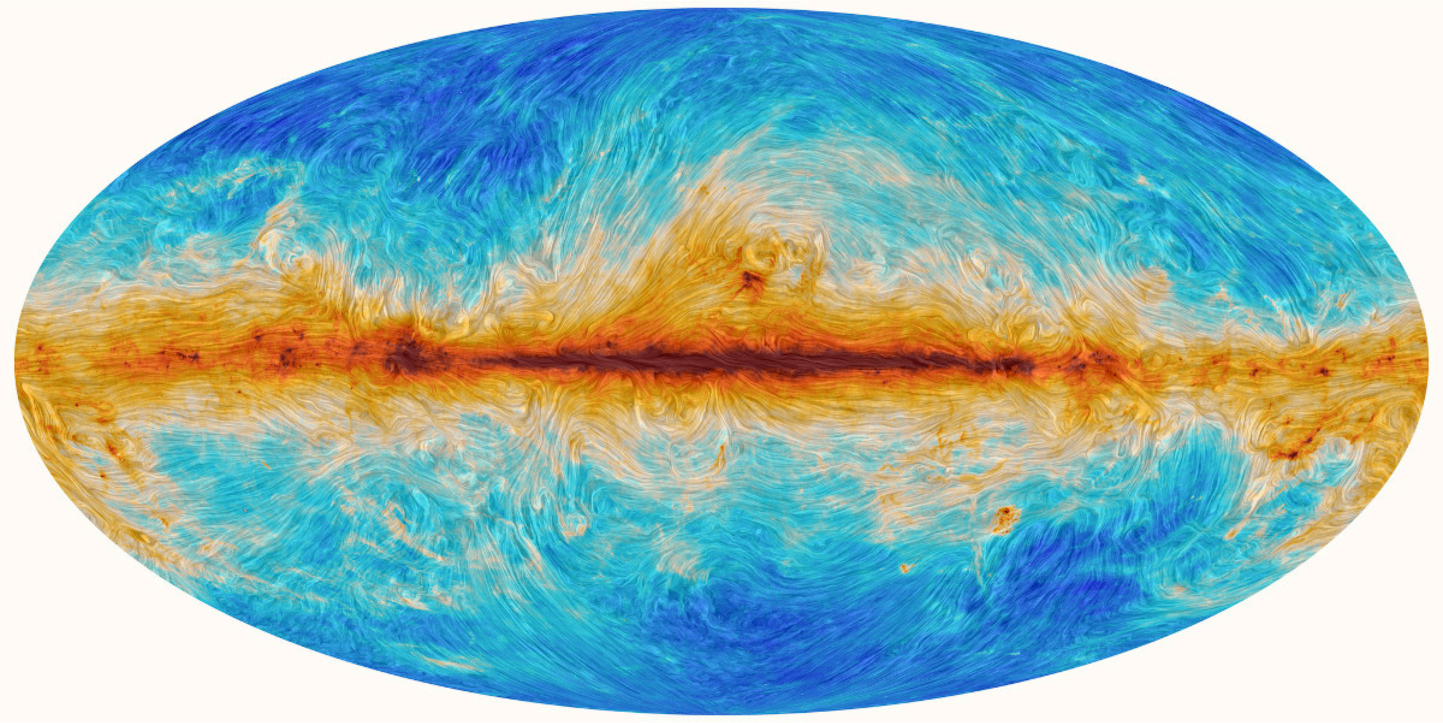
Noise and Systematics

- Signal is extremely small (<100 x T)
- Requirement: Need extremely low polarization noise level (~0.5uK', fsky~0.04)
- Low levels of systematics from beam / leakage, readout…



Foregrounds

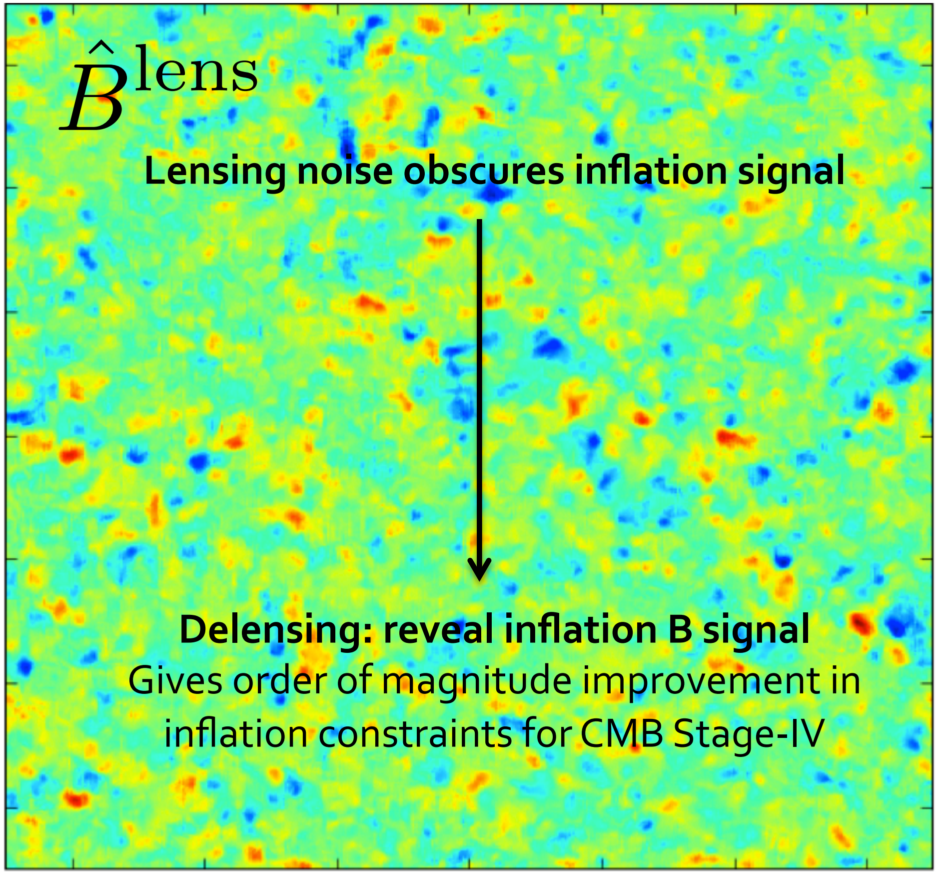
- Galactic emission also sources B-mode polarization
- **Requirement: multifrequency** data (~8+freqs.) to remove.
- How complex are foregrounds? (Decorrelation, AME, variation…?)



Planck polarized dust map

CMB Lensing Noise

- Grav. lensing of CMB also makes B; lensing noise limits measurements. How to reduce?
- Delensing: measure lensing (see later), deduce B^{lens}, and subtract
- Requirement: high-resolution, low noise (<4', ~1uK'), good delensing algorithms!



N.B. Recently, first demonstration in data! [Larsen/Challinor/Sherwin+2016, Sherwin/Schmittfull 2015]

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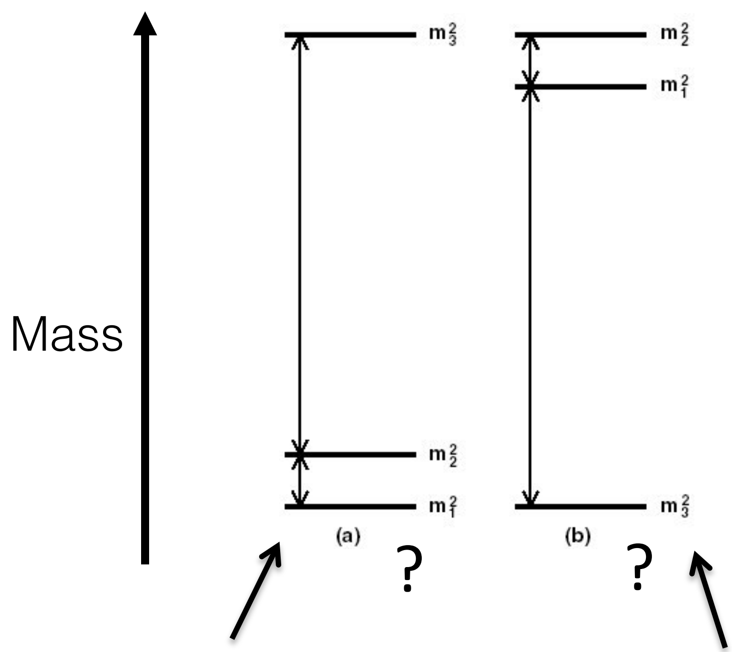
Neutrino Masses

- We know mass differences, but don't know the mass scale, or even which neutrino is heaviest (i.e. the mass ordering)
- measuring the **sum** of masses $\sum m_\nu$ will give lots of insight (ultimate goal: mechanism that gives neutrinos mass)



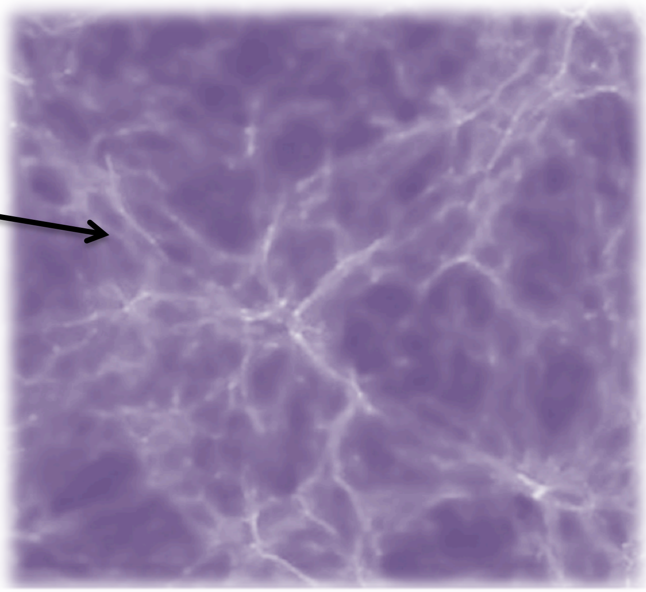
Mass sum: >60 meV >100 meV

Cosmic Neutrino Background: Changes Matter Structure Growth

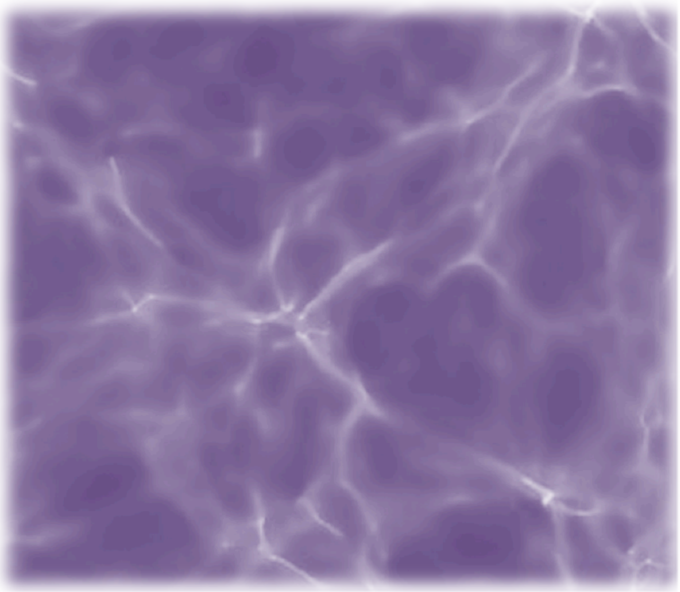
- The more massive neutrinos are, the more small scale matter structure is blurred out.

Cosmic mass distribution

Image: Viel++ 2013



Neutrino Mass Negligible



Neutrino Mass Large (qualitative)

- Small scale blurring also seen in CMB lensing map

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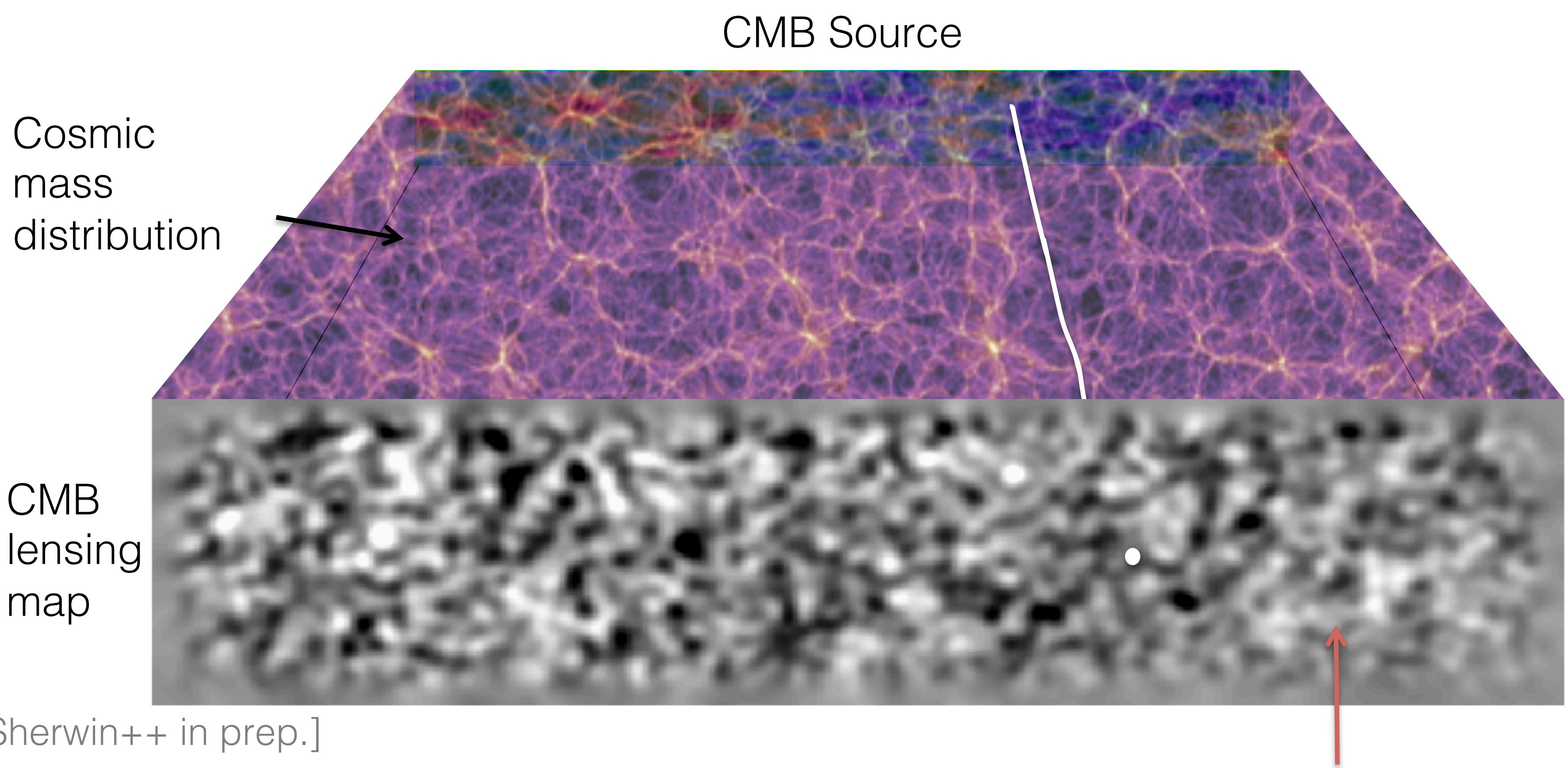


[Sherwin++ in prep.]

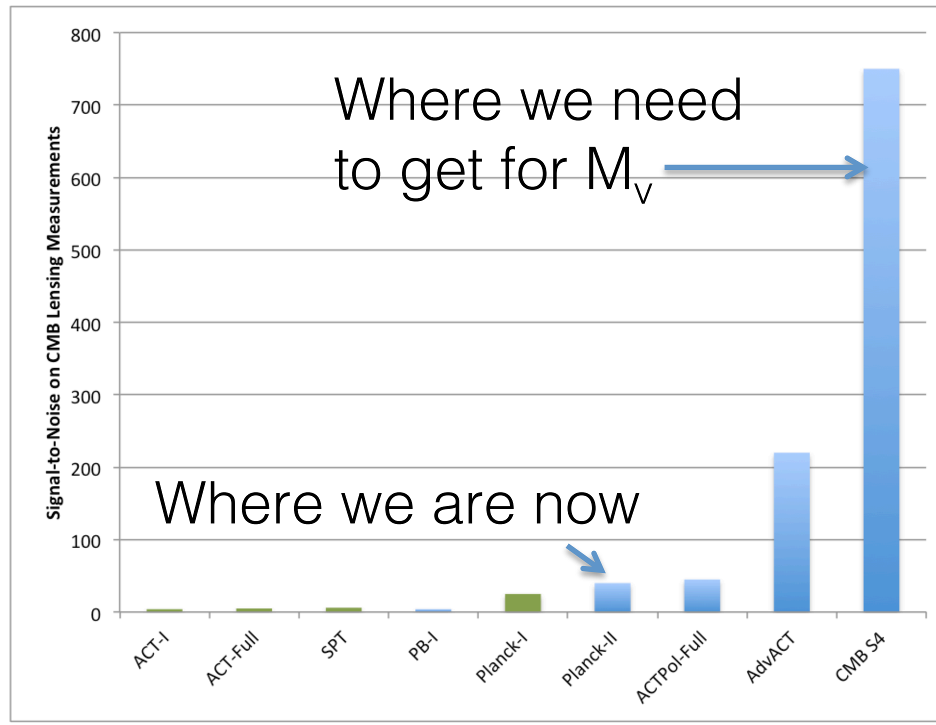
- Small scale blurring also seen in CMB lensing map

Challenges and Requirements: Lensing and Neutrino Mass

- Target ~60 meV or
  $$\sigma(\sum m_\nu) \sim 15\ \mathrm{meV}$$
- **Requirements: large area, high resolution,** low-noise (fsky~0.2,~<uK',<4') polarized CMB data for lensing (also useful for DE)

- Significant challenges in lensing data analysis and theory! But achievable (problem: tau?)

Signal-to-noise on lensing



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Light Particles and Cosmology

- Cosmic Neutrino Background: in radiation era, very large part of the energy density - 41% of total!

- Influences expansion rate H (as extra form of radiation):

$$3M_{\rm pl}^2 H^2 \simeq \rho_\gamma + \rho_\nu$$

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$$3M_{\rm pl}^2 H^2 \simeq \rho_\gamma + \rho_\nu \longleftarrow N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_\nu}{\rho_\gamma}$$

- Energy density parameterized via number of effective neutrino species $N_{\rm eff}$. Measure via CMB
  - Measure this with Planck: $N_{\rm eff} = 3.04 \pm 0.18$
  - So what? We have Z-decay measurements.

N_{eff} from Cosmology: A Universal Probe for Light Relics

- Not just sensitive to particles with the SM couplings of neutrinos
- Gravity sees everything: cosmology probes all that is neutrino like (radiation, free-streaming)

$$3M_{\mathrm{pl}}^2 H^2 \simeq \rho_\gamma + \rho_\nu$$

- Can hunt for any new light (relativistic, weakly coupled) particles!

History of an Extra Light Particle

- At high energies, weakly interacting particle is produced in thermal equilibrium. It freezes out at $T_{freeze\text{-}out}$. At first, $\Delta N_{eff} \sim 1$.

- Universe cools. Phase transition! (e.g. muons/anti-muons annihilate).

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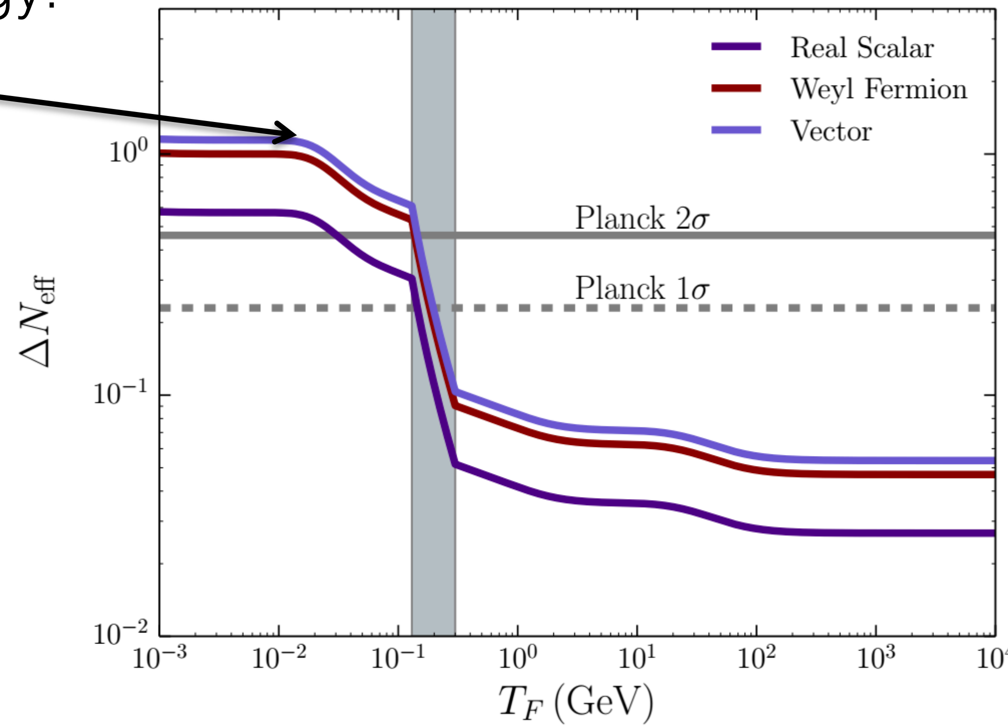
- Annihilating particles dump energy into photons not particle. ΔN_{eff} goes DOWN for every phase transition after freeze out.

$$N_{\text{eff}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

Impact on energy gets diluted

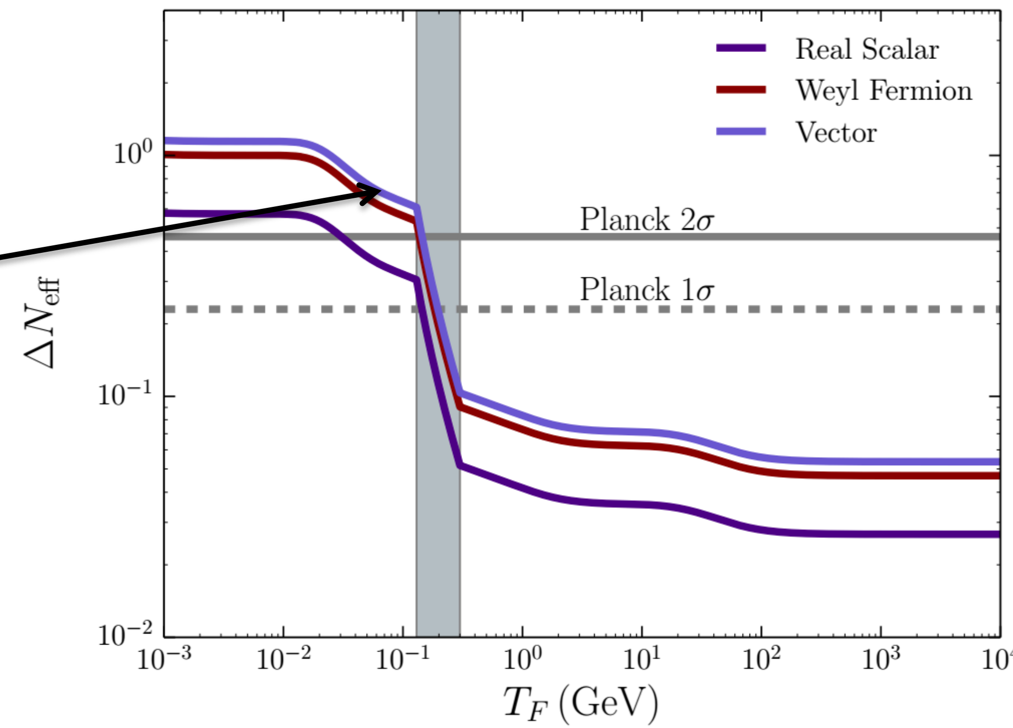
A Particle Freezes Out. How Much N_{eff} Does it Contribute?

- Freeze out late / low energy:
  $\Delta N_{eff} \sim 1$



A Particle Freezes Out.
How Much N_{eff} Does it Contribute?

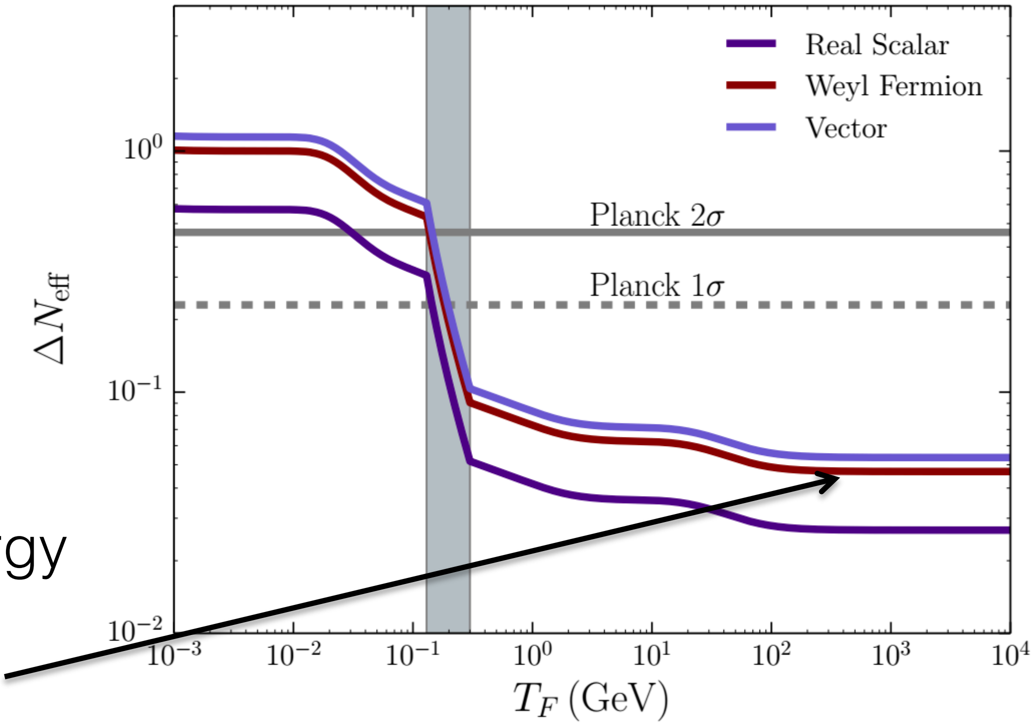
- Here, some muons (e,g.) will annihilate after freeze out: ΔN_{eff} ~0.5



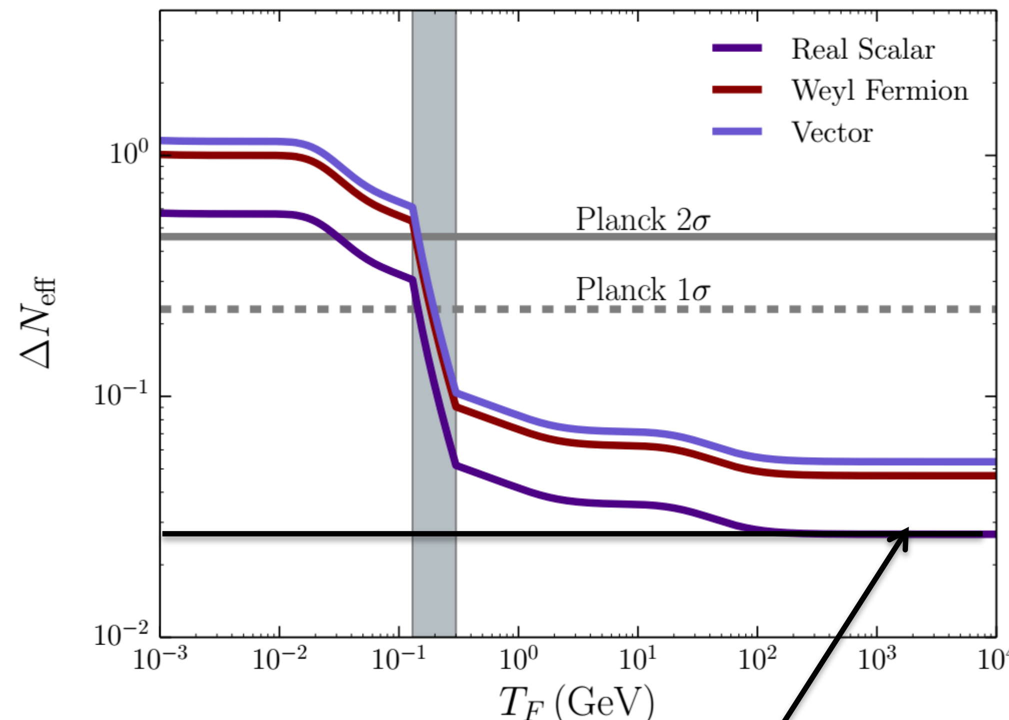
[Baumann++ 2015]

A Particle Freezes Out. How Much N_{eff} Does it Contribute?

- At high freeze-out temperature, the particle misses out on lots of energy from the QCD phase transition, so ΔN_{eff} is very small.



N_{eff}: What is the Target?

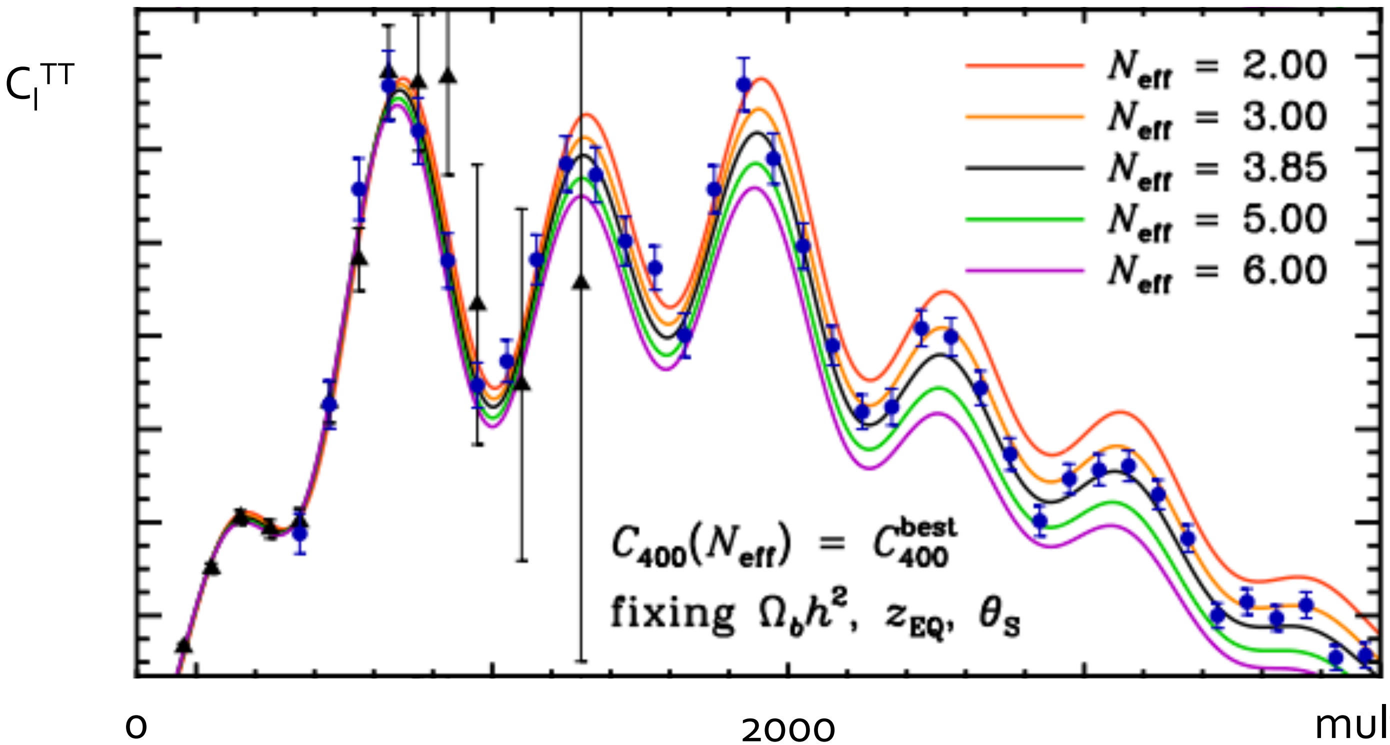


- If we can measure this: target sensitivity, can see any new light particle that was ever in equilibrium (out to reheating temp.!)

Real Scalar:	$\Delta N_{\rm eff} = 0.027$
Weyl Fermion:	$\Delta N_{\rm eff} = 0.047$
Vector boson:	$\Delta N_{\rm eff} = 0.054$

Probing N_{eff} in the CMB Power Spectra

- Change in early expansion rate > change in diffusion time > small change in damping seen in CMB power spectrum.

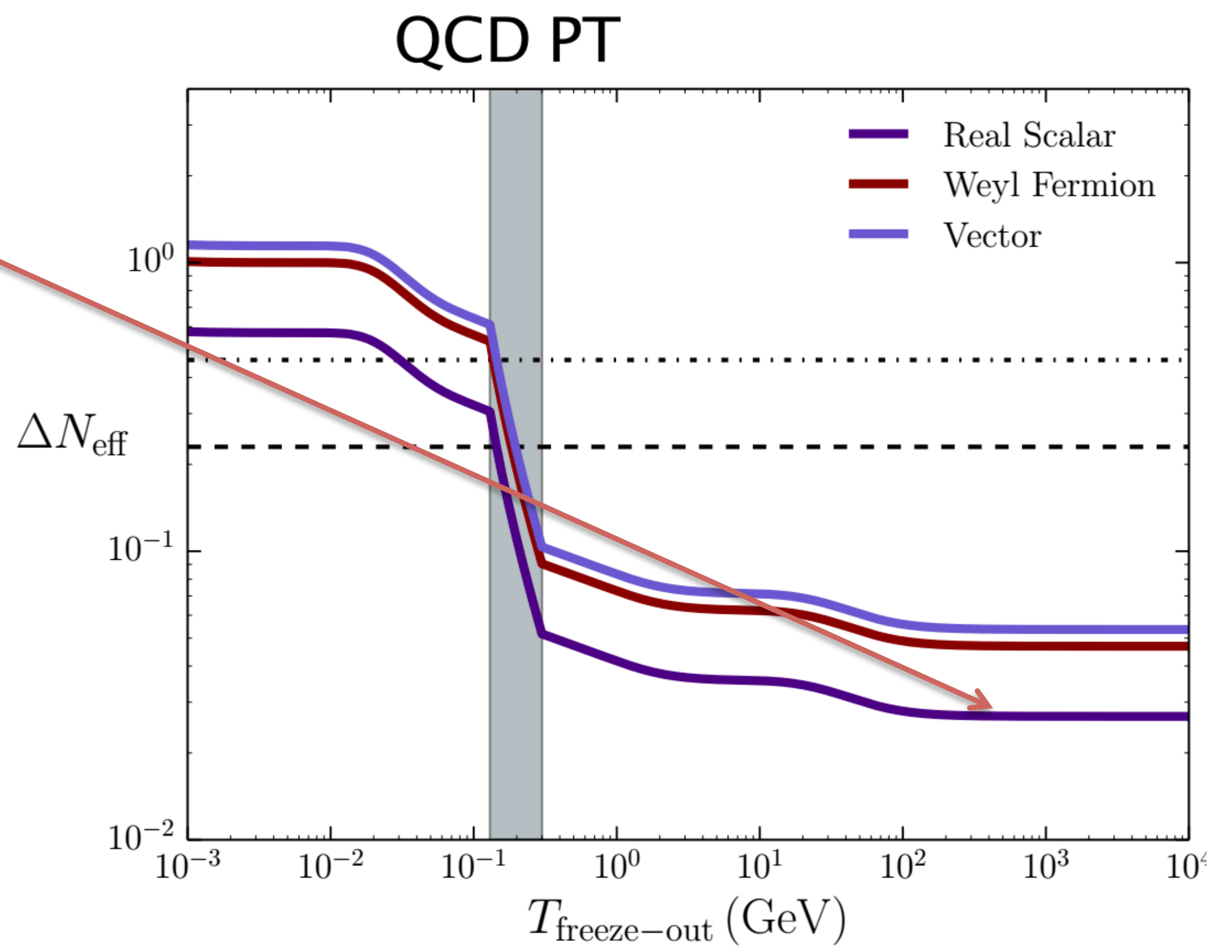


[Hou++ 2013]

- Also: small shift in phases (free-streaming). Delensing helps!

Challenges / Requirements:
High Precision Small-scale CMB Spectra

- Requirement to hit targets: Very low noise (~uK') and large sky areas (fsky~1)
- Good beam systematics control
- Or lower noise: 2 sigma, room for improvement



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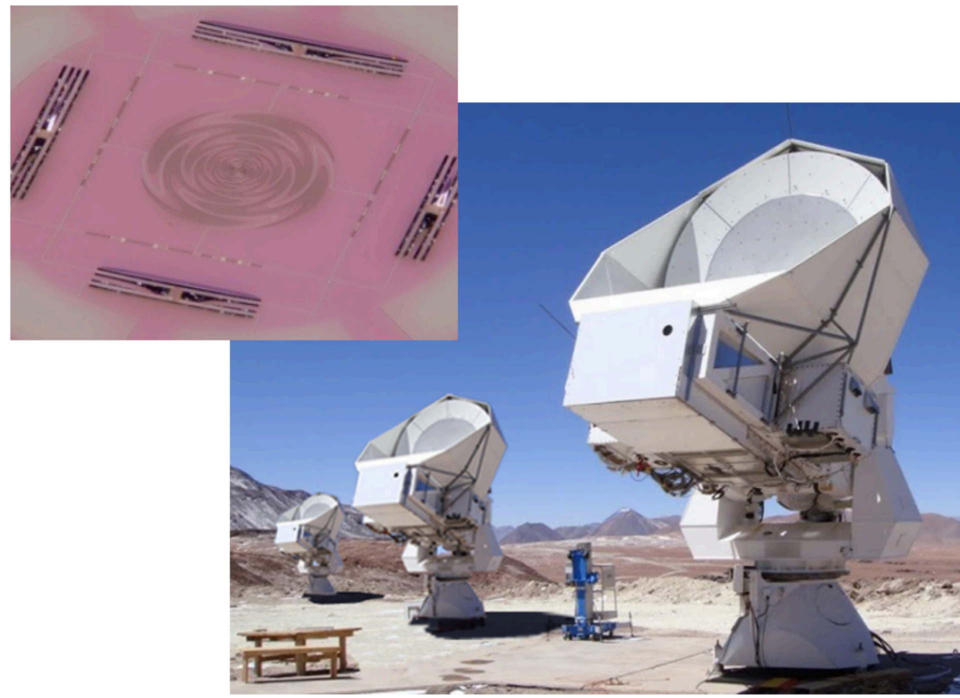
CMB Stage IV
Requirements and Challenges

- CMB-S4 is the next generation CMB survey. Requirements:
    - low noise (~1uK')
      >500000 bolometers
    - 5+ frequencies
      >multichroic pixels
    - high resolution (<4')
      >3+ meter telescope



- Main challenges: <u>scale</u> / systematics tolerance / ultra high precision data analysis

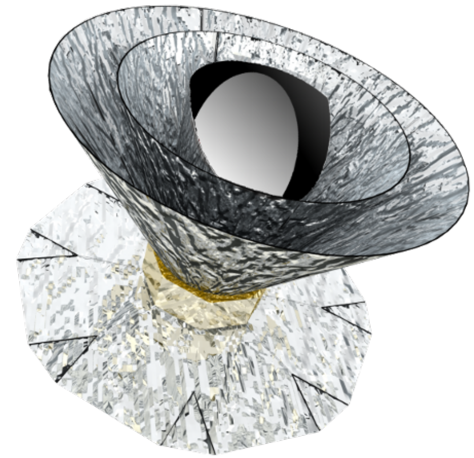
Beyond CMB-S4

- r / M_ν: need more frequency channels
  - Space mission (Litebird / PIXIE/Core…)

- N_{eff}: need lower noise over more area
  - "CMB-S5" to reach 5 sigma on minimal targets

- Spectral distortions for P(k), lines..:
  - Ultra sensitive spectrometer in space (PIXIE / PRISM-like…)

LiteBIRD (~2025-)



PRISM

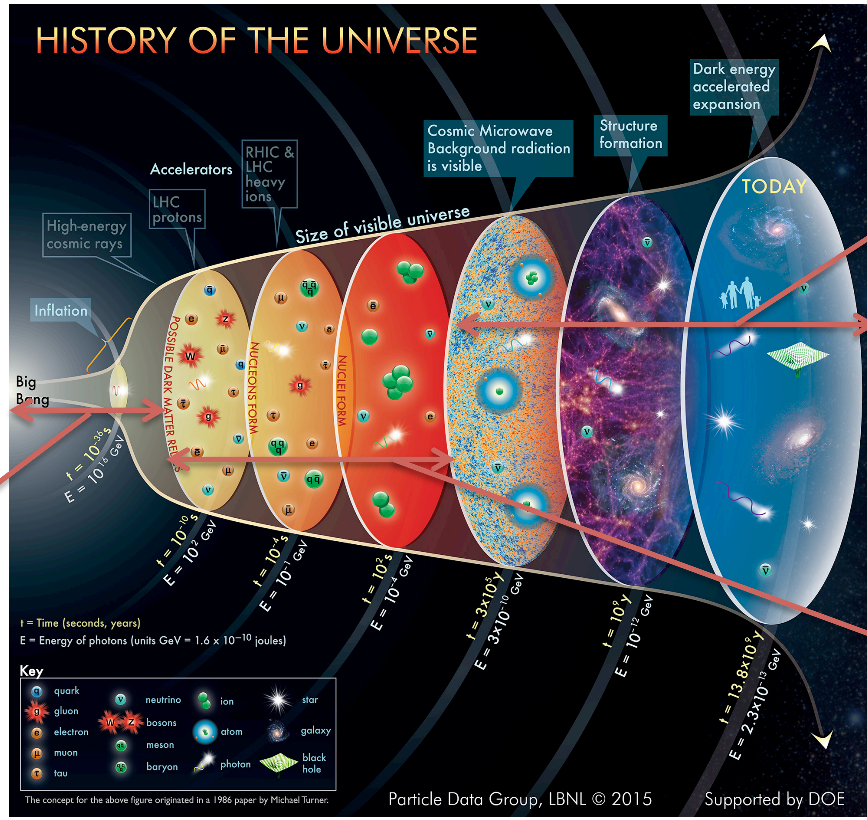
Overheard: cosmology talk, ca. 2013-2014

- “Planck will soon have observed all the modes in the CMB”

- “To learn about physics, the CMB game is over, LSS is the only way forward.”

Future CMB will Probe Physics from here to the Highest Energies and Earliest Times

With CMB-S4 and beyond, probe:



Neutrino Mass (target ~0.06eV) [and Dark Energy, cross-correlations] via Lensing

Inflation via r (target ~0.001)

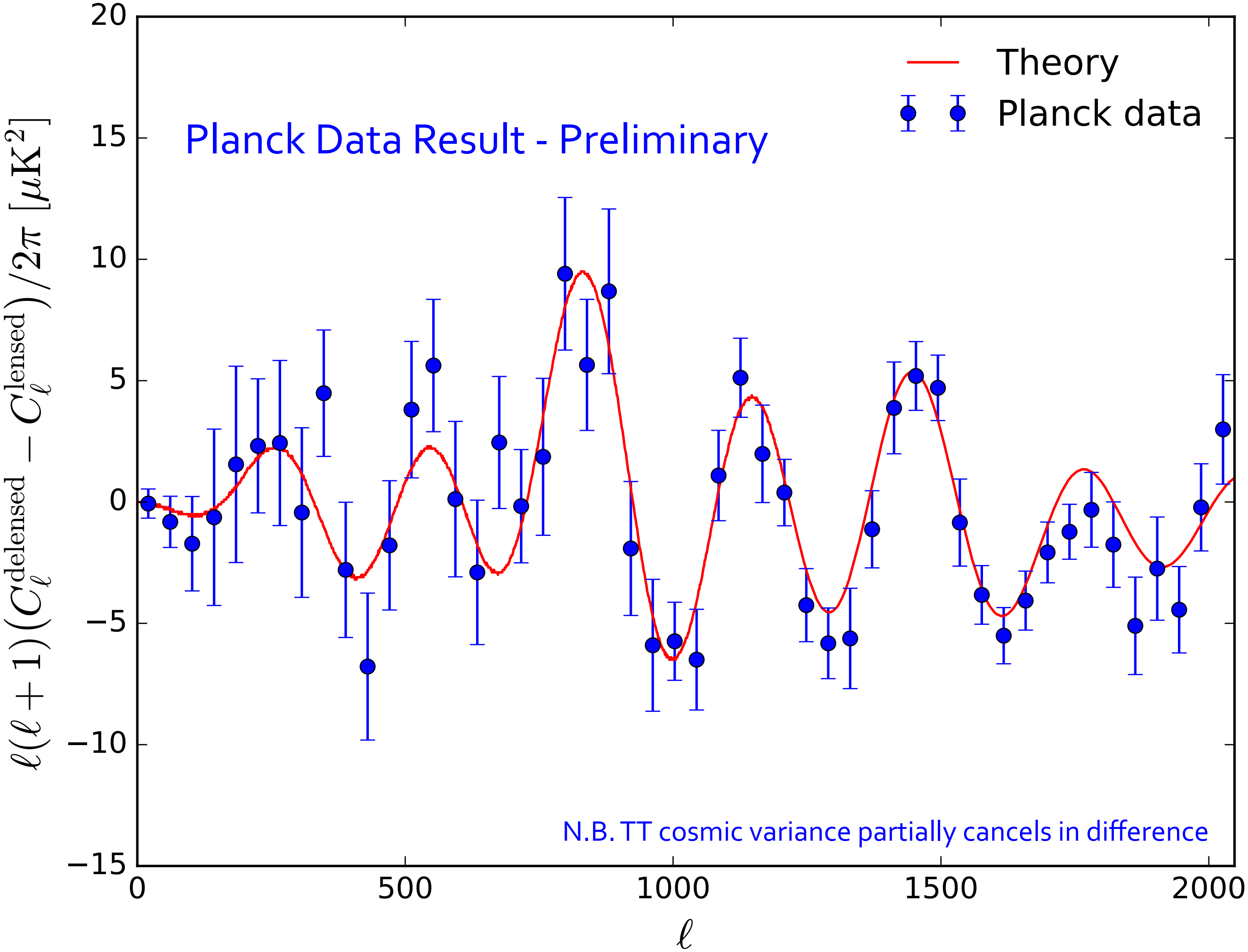
Light relics via Neff (target ~0.03)

[+spectral distortions, non-Gaussianity]

I think many of the most interesting areas of CMB physics are just beginning!

Backup Slides

Demonstrating Delensing:
Difference of Lensed and Delensed Temp. Spectra



First demonstration of delensing in data!

Lensing Measurement

$$T(\mathbf{l}) = \mathrm{FourierTransform}[T(\hat{\mathbf{n}})]$$

- Without lensing, CMB temperature modes are independent

$$\langle T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})\rangle = 0$$

- Lensing changes known statistics: introduces correlations

$$\langle T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})\rangle \sim d(\mathbf{L})$$

- So: measure lensing by looking for these correlations in temp.

$$\hat{d}(\mathbf{L}) \sim \int d^2\mathbf{l}\; T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})$$

[Hu, Okamoto 2002]

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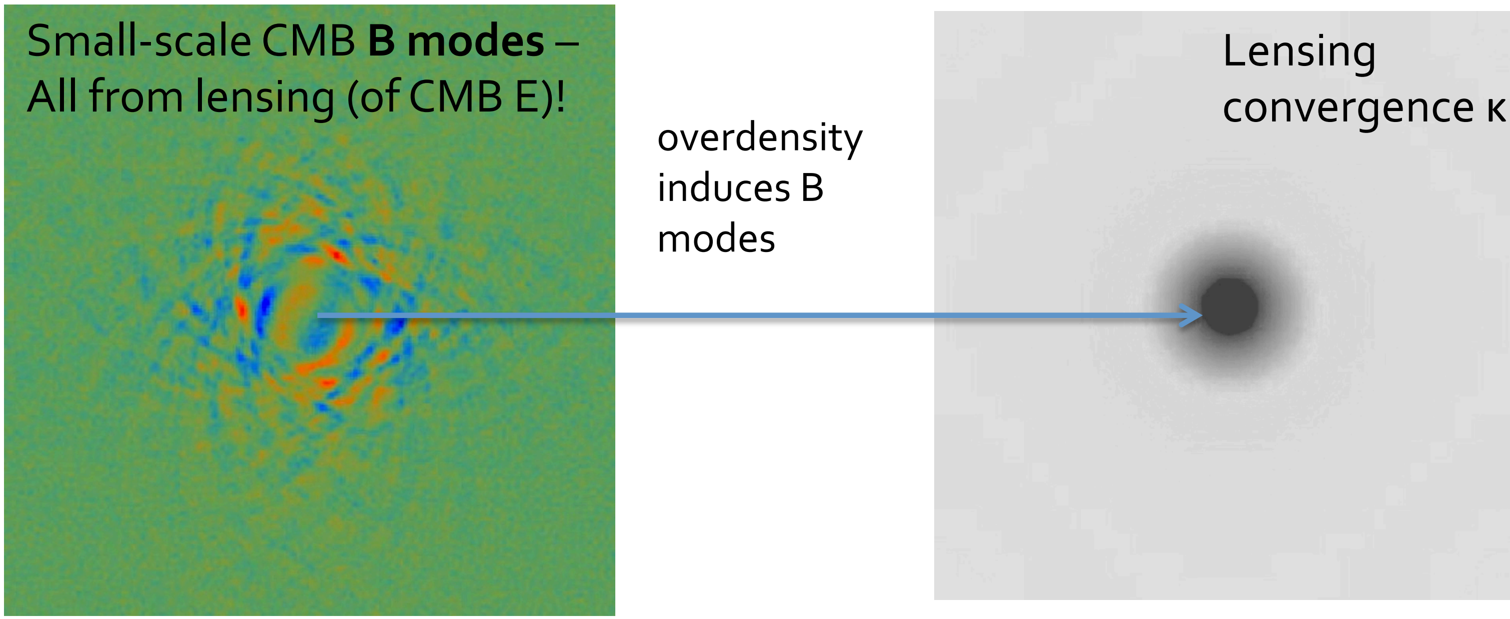
$$\hat{d}(\mathbf{L}) \sim \int d^2\mathbf{l}\; T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})$$

and polarization

$$\hat{d}(\mathbf{L}) \sim \int d\mathbf{l}\; E(\mathbf{l})B^*(\mathbf{l}-\mathbf{L})$$

[Hu, Okamoto 2002]

Measuring CMB Lensing Convergence: An Approximate Picture

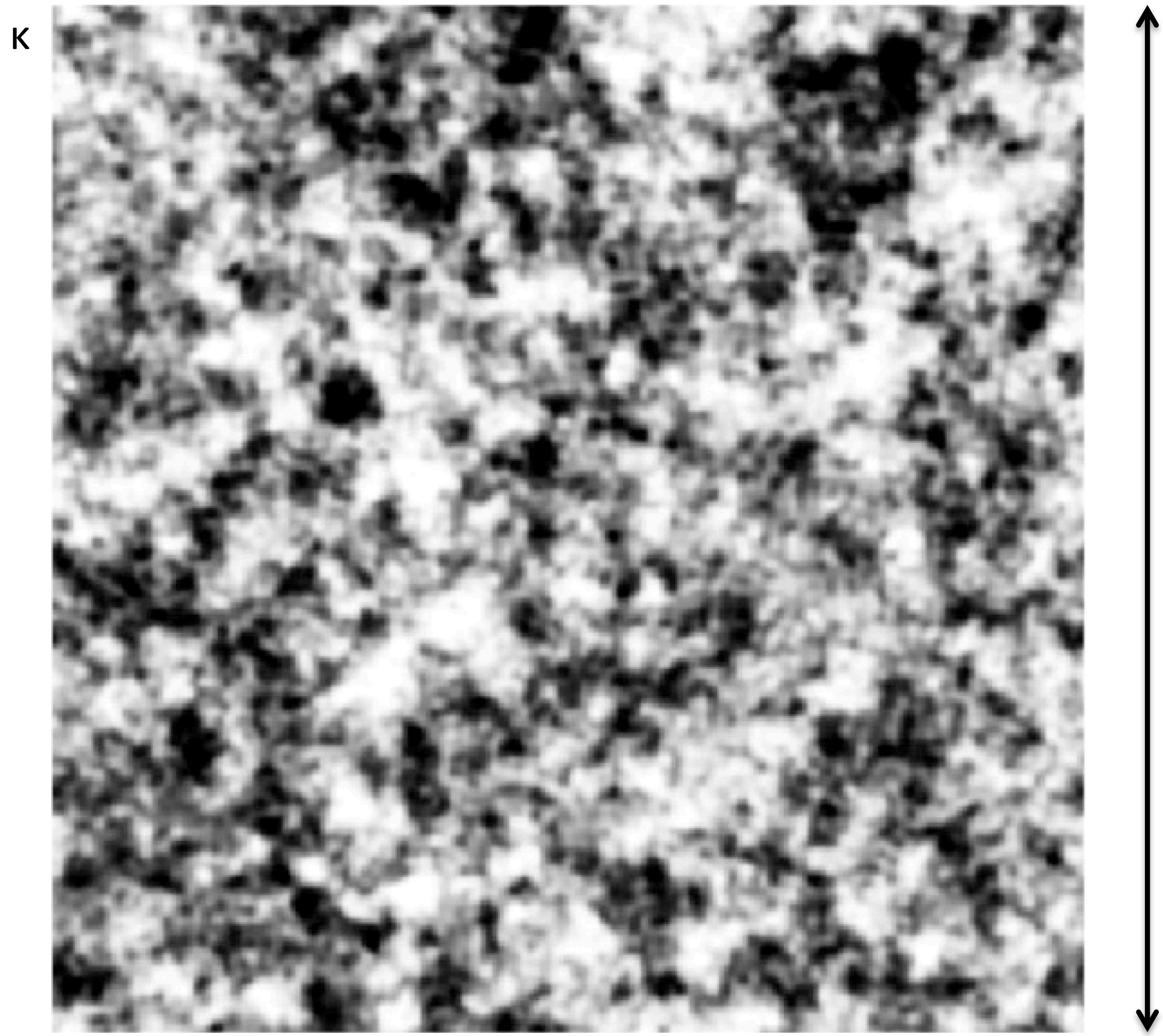


[Hu, Okamoto 2002]

look for lensing-induced correlations of E and B (delens, iterate, for higher signal-to-noise)

CMB Lensing Convergence Measurement

True Lensing:
(Simulation input, 1uK' CMB noise)

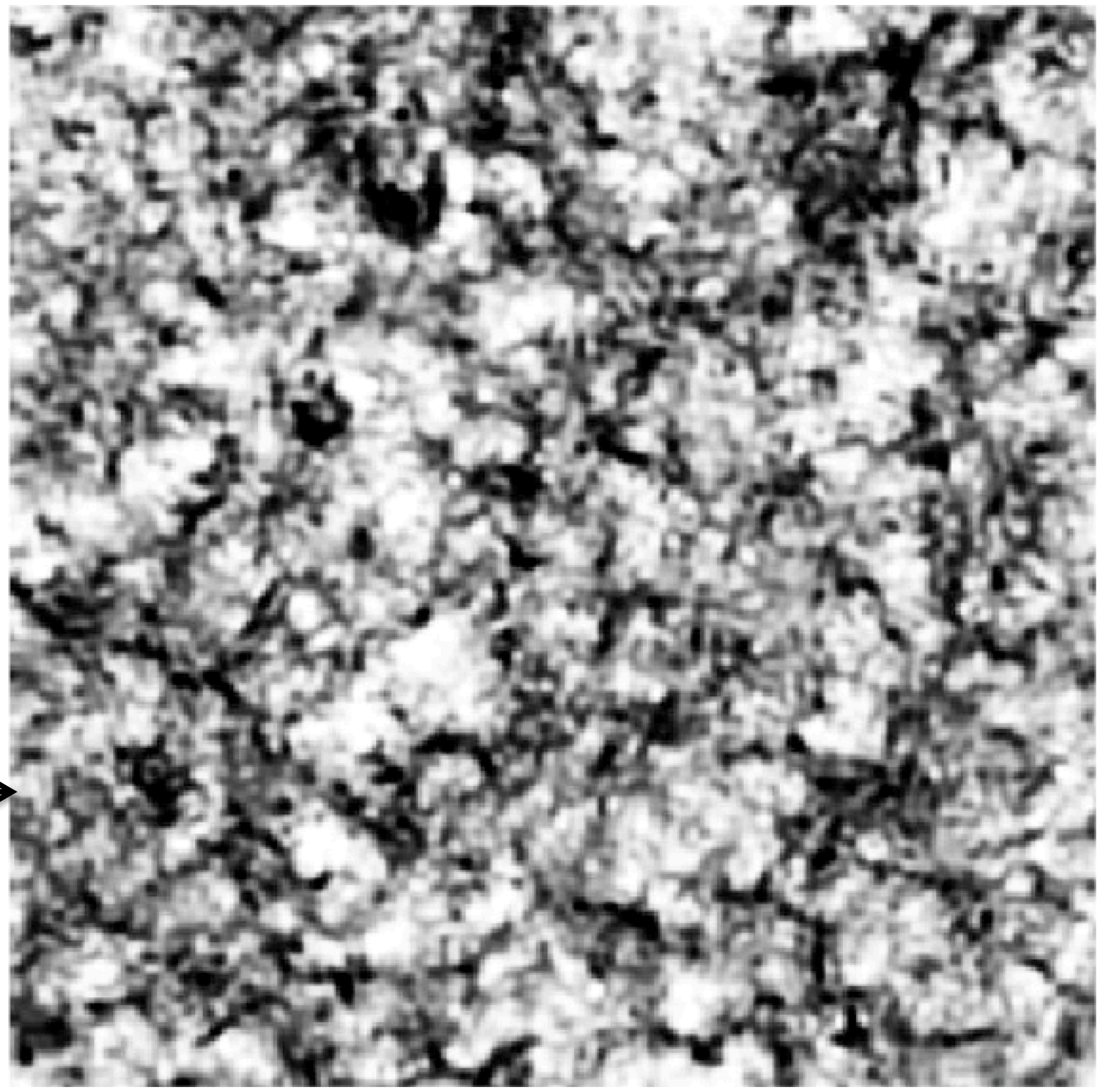


CMB Lensing Convergence Measurement

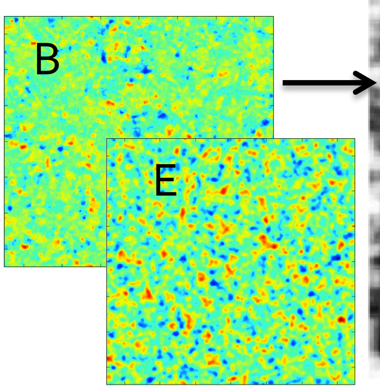
Recovered lensing

For S4, over much of the sky! (~1/2?)

κ



10 degrees



[pipeline: Sherwin++ in prep. 2016]